

# Constraints on a Stochastic Background of Primordial Magnetic Fields with WMAP and South Pole Telescope data

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We constrain a stochastic background of primordial magnetic fields (PMF) by its contribution to the cosmic microwave background (CMB) anisotropy angular power spectrum with the combination of WMAP 7 year and South Pole Telescope (SPT) data. The contamination in the SPT data by unresolved point sources and by the Sunyaev Zeldovich (SZ) effect due to galaxy clusters has been taken into account as modelled by the SPT collaboration. With this combination of WMAP 7 yr and SPT data, we constrain the amplitude Gaussian smoothed over 1 Mpc scale of a stochastic background of non-helical PMF to  $B_{1\text{Mpc}} < 3.5$  nG at 95% confidence level. Our analysis shows that SPT data up to  $\ell = 3000$  bring an improvement of almost a factor two with respect to results with previous CMB high- $\ell$  data. We then discuss the forecasted impact from unresolved points sources and SZ effect for PLANCK capabilities in constraining PMF.

## I. INTRODUCTION

The origin of the large scale magnetic fields observed in galaxies and clusters of galaxies is an open issue of great importance in modern astrophysics. The dynamo effect provides a mechanism to explain the observed magnetic fields associated to galaxies, whereas those associated to clusters may be generated by the amplification of small fields due to gravitational compression. Both these mechanisms might require an initial magnetic seed, although with different amplitude and different correlation length for galaxies and clusters.

In addition to observations of unusually strong magnetic field in galaxies at high redshift [1, 2], recently high energy observations from FERMI added a significant piece to the puzzle of extragalactic magnetic fields. The presence of diffuse extra-galactic magnetic fields in intercluster voids is proposed to justify the low flux of GeV photons from distant TeV blazars [3, 4, 5, 6, 7]. These data pose a *lower* limit of the order of  $10^{-18} - 10^{-15}$  Gauss to the amplitude of extragalactic magnetic fields. Such extra-galactic magnetic fields in voids are compatible either with a primordial origin or an efficient transport mechanism for magnetic fields in galaxies. Therefore, the high energy observations by FERMI are not in contradiction with a primordial origin of extra-galactic magnetic fields.

Current CMB anisotropy measurements lead to upper limits on the amplitude of a stochastic background of primordial magnetic fields generated before nucleosynthesis [8, 9, 10, 11, 12] (see Ref. [13] for a treatment claiming much tighter constraints). Indeed, a stochastic background of PMF generates all types of magnetized linear perturbations [14, 15]: scalar [8, 14, 15, 16, 17, 18,

19, 20], vector [21, 22, 23] and tensor [22, 24, 25] and all these contribute to the CMB anisotropy pattern in temperature and polarization. PMF modelled as a fully inhomogeneous component have also a fully non-Gaussian contribution to CMB anisotropies with a non zero higher statistical moments, which can be used as useful probes, such as the magnetized bispectrum [26, 27] and the magnetized trispectrum [28].

In our previous works [10, 14, 19] we have refined the computation of magnetized CMB anisotropies keeping into account only relativistic degrees of freedom and the correlators for the Fourier transforms of the EMT in presence of a sharp cut-off which mimics the damping scale due to viscosity [14, 19]. In the most recent work [10] we have computed the constraints coming from CMB data by WMAP7 in combination with data from ACBAR [29], QUaD [30] and BICEP [31] updating previous investigations [8, 9, 12].

In this work we use the publicly available CMB anisotropy data at high multipoles as those from the South Pole Telescope (SPT) [32, 33] to further constrain a stochastic background of PMF. See Ref. [34] for an analogous constraint on another important high- $\ell$  contribution to CMB anisotropies such as cosmic strings. Constraints on PMF from anisotropies at high multipoles,  $\ell \sim 3000$ , are not a straightforward extension of what derived at smaller angular scales: Right at those angular scales where the Silk damping suppresses the standard primary CMB fluctuations, the dominant contribution of PMF and other non-standard cosmological models (such as cosmic strings) is polluted by extragalactic contamination and secondary anisotropies, such as Sunyaev-Zeldovich. In order to fully exploit small scale CMB data to constrain physics which produce CMB contributions which are not erased by the Silk damping, it is necessary to model carefully the residual foreground contamination to the angular power spectrum.

The paper is organized as follows. In section II we summarize the general properties of PMF and the methodol-

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ogy based on Refs. [10, 14, 19] to compute their contribution to CMB anisotropies. In Section III we briefly introduce the contamination of foreground and secondary residuals at high multipoles in the perspective of SPT data. In Section IV we present and discuss the results obtained with WMAP 7 + SPT data. In Section V we discuss the impact of foreground and secondary residuals at high multipoles on the PLANCK capabilities to constrain a stochastic background of PMF and in section VI we draw our conclusions.

## II. STOCHASTIC BACKGROUND OF PMF AND MAGNETIZED CMB ANISOTROPIES

In this section we summarize the methodology used in our previous papers to compute the PMF contribution to CMB anisotropies. We model a stochastic background of PMF as a fully inhomogeneous component with a power-law power spectrum  $P_B(k) = A k^{n_B}$ , where  $A$  is the amplitude and  $n_B$  is the spectral index. Our convention for the Fourier transform of the two point correlation function for a stochastic background is:

$$\langle B_i(\mathbf{k}) B_j^*(\mathbf{k}') \rangle = (2\pi)^3 \delta(\mathbf{k} - \mathbf{k}') (\delta_{ij} - \hat{k}_i \hat{k}_j) \frac{P_B(k)}{2} \quad (1)$$

where  $n_B > -3$ . We assume the MHD limit in which  $B(\mathbf{x}, \tau) = B(\mathbf{x})/a(\tau)^2$  with  $a(\tau)$  being the scale factor (normalized to  $a_0 = 1$  today) and  $\tau$  the conformal time. As convention, we use the amplitude of the magnetic fields smoothed over  $\lambda$ :

$$B_\lambda^2 = \int_0^\infty \frac{dk k^2}{2\pi^2} e^{-k^2 \lambda^2} P_B(k) = \frac{A}{4\pi^2 \lambda^{n_B+3}} \Gamma\left(\frac{n_B+3}{2}\right) \quad (2)$$

PMF survive the Silk damping but are damped on smaller scales by radiation viscosity [21, 35]. We modelled this damping with a sharp cut off in the power spectrum at the scale [21, 35]:

$$k_D = (2.9 \times 10^4)^{\frac{1}{n_B+5}} \left(\frac{B_\lambda}{\text{nG}}\right)^{\frac{-2}{n_B+5}} \left(\frac{2\pi}{\lambda/\text{Mpc}}\right)^{\frac{n_B+3}{n_B+5}} h^{\frac{1}{n_B+5}} \text{Mpc}^{-1} \quad (3)$$

A stochastic background of PMF acts as a fully inhomogeneous source to metric scalar, vector and tensor perturbations. The source terms are given by the PMF energy momentum tensor and Lorentz Force in Fourier

space [22, 24]:

$$|\rho_B(k)|^2 = \frac{1}{1024\pi^5} \int_\Omega d\mathbf{p} P_B(p) P_B(|\mathbf{k} - \mathbf{p}|) (1 + \mu^2) \quad (4)$$

$$|\Pi^{(V)}(k)|^2 = \frac{1}{512\pi^5} \int_\Omega d\mathbf{p} P_B(p) P_B(|\mathbf{k} - \mathbf{p}|) \times [(1 + \beta^2)(1 - \gamma^2) + \gamma\beta(\mu - \gamma\beta)] \quad (5)$$

$$|\Pi^{(T)}(k)|^2 = \frac{1}{512\pi^5} \int_\Omega d\mathbf{p} P_B(p) P_B(|\mathbf{k} - \mathbf{p}|) \times (1 + 2\gamma^2 + \gamma^2\beta^2), \quad (6)$$

$$|\mathbf{L}_B(k)|^2 = \frac{1}{128\pi^2} \int_\Omega d\mathbf{p} P_B(p) P_B(|\mathbf{k} - \mathbf{p}|) \times (1 + \mu^2 + 4\gamma\beta(\gamma\beta - \mu)), \quad (7)$$

where  $\mu = \hat{\mathbf{p}} \cdot (\mathbf{k} - \mathbf{p})/|\mathbf{k} - \mathbf{p}|$ ,  $\gamma = \hat{\mathbf{k}} \cdot \hat{\mathbf{p}}$ ,  $\beta = \hat{\mathbf{k}} \cdot (\mathbf{k} - \mathbf{p})/|\mathbf{k} - \mathbf{p}|$  and  $\Omega$  denotes the volume with  $p < k_D$ .

The analytical exact results for the PMF EMT spectra were given for specific values of  $n_B$  in [14, 19]. As in our previous work [10] we use accurate approximations for the power spectra of  $\rho_B$ ,  $\mathbf{L}_B$ ,  $\Pi^V$  which are created to calculate the PMF contribution to CMB anisotropies in a continuous range of  $n_B$ . We use the initial conditions for cosmological fluctuations as given in [10, 14]. For scalar perturbations we consider the compensated mode described in [10, 14, 19]. The scalar magnetized perturbations are the dominant PMF contribution to CMB anisotropies on large and intermediate angular scales, whereas the vector magnetized perturbations represent the dominant PMF contribution on small angular scales. On these scales the primary CMB is suppressed by the Silk damping, making the vector magnetic mode the dominant contribution to the angular power spectrum as shown in Fig. 1. To constrain the PMF amplitude we neglect the tensor contribution, since it is subdominant with respect to scalar and vector ones [10, 14].

## III. ASTROPHYSICAL CONTAMINATION OF CMB DATA ON SMALL ANGULAR SCALES

It is well understood and proved that CMB data are a fundamental tool to constrain a stochastic background of PMF. Considering the nature of their impact on CMB angular power spectrum, which is mainly on small angular scales and dominated by the vector contribution, it is obvious that higher the resolution of the data tighter should be the constraints on PMF. But data on small angular scales are also affected by contamination from astrophysical sources. In particular for SPT data the astrophysical contamination is given by residual extragalactic point sources and cluster of galaxies. The residual point sources contribution strongly depends on the frequency considered: frequencies lower than 90-100 GHz are mainly dominated by radiogalaxies whereas frequencies greater than 200 GHz are dominated by infrared

galaxies, the frequencies inbetween are affected by both contributions [36]. Both radio and infrared galaxies contribute with a Poissonian term which is due to their random distribution in the sky. The Poissonian term is simply given by a flat angular power spectrum whose amplitude is determined by the source number counts integrated in flux densities and the flux density detection threshold [37, 38, 39]. Infrared galaxies together with the Poissonian term contributes also with a clustering term. The clustering is much more complex than the Poissonian term, it grows with the frequency and becomes the dominant component for higher frequencies. It depends on the properties of infrared galaxies, on their redshift, on the bias and on the cosmological model, and can be modelled in different ways with increasing complexity [36, 37, 40, 41, 42]. The galaxy clusters contribute with the Sunyaev-Zeldovich effect (SZ) which can be divided into thermal [43] and kinetic [44] contributions. In the case of SPT data both contributions have been considered in a single SZ term [32].

For our analysis we use the templates given by the SPT collaboration for the 150 GHz data [32, 45]. The templates are characterized by one amplitude parameter each, therefore we account for three new parameters in the analysis.

In the third panel of Fig. 1 we show the shapes of the the three astrophysical contributions, Poissonian, clustering and SZ effect. The flat shape of the clustering term on large scales is given in the template provided by the SPT collaboration which considers a shape variation only on multipoles where the clustering contribution is relevant, assuming a flat contribution elsewhere, considering that for the SPT data release used the lowest multipole is  $\ell \sim 650$ .

In the last panel of Fig. 1 we compare the spectral shapes of typical scalar and vector magnetic modes with an amplitude of 6 nG and a spectra index of -2.5 with the sum of the three astrophysical contributions. We note how both astrophysical and PMF contributions are comparable in the same range of multipoles.

#### IV. RESULTS

In the present work we derive the constraints on PMF performing a combined analysis of the WMAP 7 year [46, 47] and SPT data following Ref. [32].

We use the latest WMAP likelihood code (version v4p1) and associated data available at <http://lambda.gsfc.nasa.gov/>. We modify the WMAP likelihood by excluding the temperature bandpowers between  $\ell = 800$  and 1200. We use the SPT data release relative to the observation of 790 square degrees of the sky at 150 GHz during 2008 and 2009. The data spans the  $\ell$  range from 650 to 3000. In order to decrease the correlations between the two data sets we excluded the SPT bandpowers for  $\ell < 800$  and we used WMAP 7 years data in temperature up to  $\ell = 800$ .

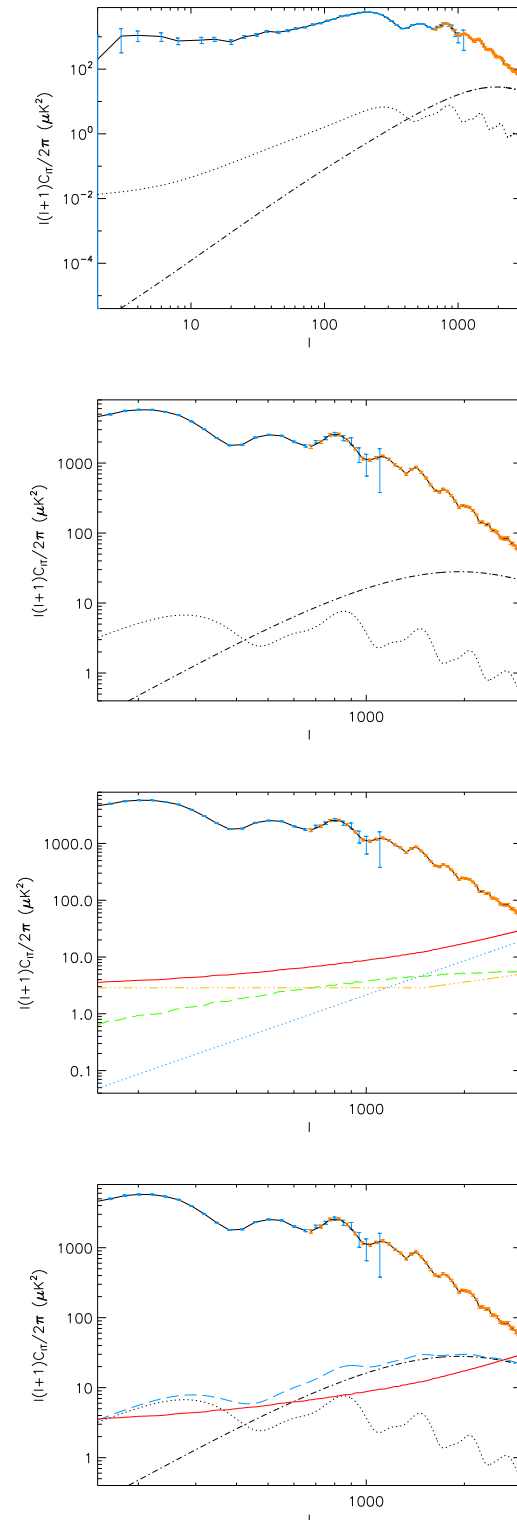


FIG. 1. Comparison of magnetized modes for a field of  $B_{1 \text{ Mpc}} = 6 \text{ nGauss}$  and  $n_B = -2.5$  with the astrophysical contributions from SPT 150 GHz data as in [32, 45]. From top to bottom. First panel shows the WMAP (blue dots) and SPT (yellow dots) data compared with scalar (dotted line) and vector (dot-dashed line) magnetic modes. The second panel is simply an high  $\ell$  focus of the first. The third panel shows the astrophysical contributions: SZ effect (dashed green line), the Poissonian term (dotted blue line), the clustering term (triple dot-dashed yellow line) and the solid red line represents the sum of the three. In the last panel the magnetic contributions including the uncorrelated sum of the two (dashed line) is compared with the total astrophysical contribution (solid line).

We develop an extension of *CosmoMC* [48] in order to compute the Bayesian probability distribution of cosmological parameters, including the magnetic ones. In order to use the small scale SPT data we introduced the contribution of astrophysical contaminations following the scheme given by the SPT collaboration [32]. We modified the code following the indications given in [45].

We vary the baryon density  $\omega_b = \Omega_b h^2$ , the cold dark matter density  $\omega_c = \Omega_c h^2$  (with  $h$  being  $H_0/100\text{km s}^{-1}\text{Mpc}^{-1}$ ), the reionisation optical depth  $\tau$  (not to be confused with the conformal time  $\tau$ ), the ratio of the sound horizon to the angular diameter distance at decoupling  $\theta$ ,  $\ln(10^{10} A_S)$ ,  $n_s$  and the magnetic parameters  $B_{1\text{Mpc}}$  (in units of 10nG) and  $n_B$ . As priors we use  $[0, 10]$  for  $B_{1\text{Mpc}}/(10\text{nG})$  and  $[-2.9, 3]$  for  $n_B$  ( $> -3$  in order to avoid infrared divergencies in the PMF EMT correlators). Together with cosmological and magnetic parameters we varied also the parameters describing the astrophysical residual contributions :  $D_{3000}^{SZ}$ ,  $D_{3000}^{PS}$ ,  $D_{3000}^{CL}$ . We used the prior  $[0, 100]$  for the three astrophysical parameters.

We assume a flat universe, a CMB temperature  $T_{\text{CMB}} = 2.725$  K and we set the primordial Helium fraction to  $y_{\text{He}} = 0.24$ . We restrict our analysis to three massless neutrinos (a non-vanishing neutrino mass leads to a large scale enhancement in the power spectrum of CMB anisotropies in the presence of PMF [15] and would not change our results). The pivot scale of the primordial scalar was set to  $k_* = 0.05 \text{ Mpc}^{-1}$ . In order to match the data we lensed the primary CMB angular power spectrum using the lensing tool included in *CosmoMC*, we have not considered the lensing of magnetized angular power spectrum. We sample the posterior using the Metropolis-Hastings algorithm [49] generating four parallel chains and imposing a conservative Gelman-Rubin convergence criterion [50] of  $R - 1 < 0.01$ .

The results of the analysis performed with the combination of WMAP 7 and SPT data are shown in Fig. 2. The constraints on cosmological parameters are in agreement with the one obtained in [32] since as shown in [10] PMF contributions do not modify the constraints on standard parameters. Concerning the PMF parameters we obtained  $B_{1\text{Mpc}} < 3.5 \text{ nG}$  and  $n_B < -0.25$  at 95% confidence level.

Contrary to what might be expected from a mere angular power spectrum point of view, the magnetic parameters are not strongly degenerate with the astrophysical ones. In fact in Fig. 3 we show the distribution of the astrophysical parameters versus the magnetic ones and note that there is no degeneracy between the astrophysical models and the magnetic modes. This holds for the multipole range of the data considered here.

We note the improvement given by SPT with respect to our previous analysis with WMAP 7 and a combination of small angular scale data [10] which included ACBAR [29], BICEP [31] and QUaD [30]. We considered ACBAR [29] data up to  $\ell = 2000$ . As far as astrophysical residual contamination in WMAP 7 and ACBAR are con-

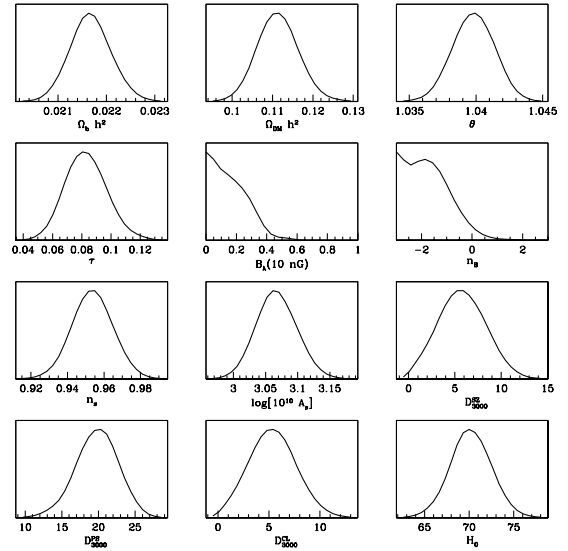


FIG. 2. Constraints with WMAP 7+SPT data, in the analysis we included the six  $\Lambda$ CDM cosmological parameters the two magnetic ones,  $B_{1\text{Mpc}}$  and  $n_B$ , but also the astrophysical ones:  $D_{3000}^{SZ}$ ,  $D_{3000}^{PS}$ ,  $D_{3000}^{CL}$ .

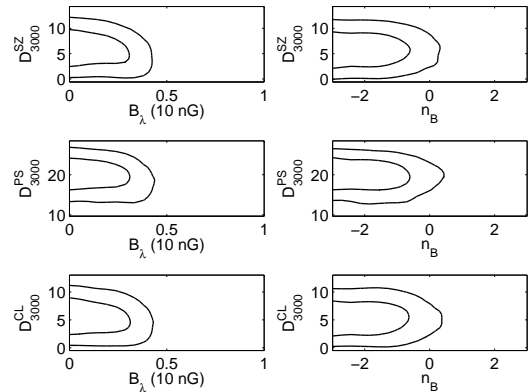


FIG. 3. Constraints with WMAP 7+SPT data for the two magnetic parameters,  $B_\lambda$  and  $n_B$ , versus the astrophysical ones:  $D_{3000}^{SZ}$ ,  $D_{3000}^{PS}$ ,  $D_{3000}^{CL}$ .

cerned, in Ref. [10] we relied on the treatment provided with the likelihoods which internally account for point source residuals, whereas for the TSZ we adopted the standard nuisance parameter which represents the amplitude of the TSZ signal, assuming the Komatsu-Seljak template based on [51] scaled accordingly to the WMAP and ACBAR frequencies. With that analysis we derived the following constraints on the amplitude and spectral index of PMF:  $B_{1\text{Mpc}} < 5.0 \text{ nG}$  and  $n_B < -0.12$  at 95% confidence level. Similar CMB constraints - of the order of 6 nG at 95% confidence level - with similar data sets were obtained in [12].

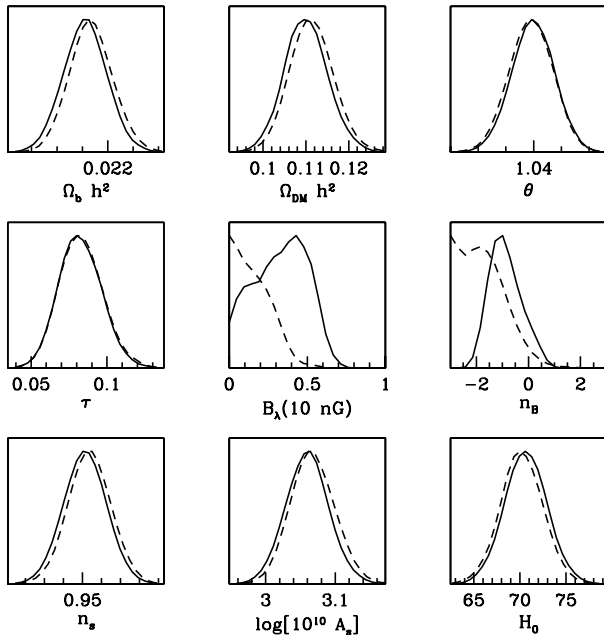


FIG. 4. Constraints with WMAP 7+SPT data, without the inclusion of astrophysical residual contributions. In the analysis we included only the six  $\Lambda$ CDM cosmological parameters the two magnetic ones,  $B_\lambda$  and  $n_B$ . Dashed lines are for comparison the results of the analysis which includes the astrophysical contribution.

#### A. Importance of astrophysical residuals for magnetic parameters

To investigate the importance of the astrophysical contamination of small scale data for the PMF constraints we performed an analysis with the same combination of WMAP 7 and SPT data as the previous one but without taking into account the astrophysical residual contributions to the angular power spectrum, which means setting all the three astrophysical parameters to zero. In Fig. 4 we show the results of the analysis, we note how thought there is no degeneracy between magnetic and astrophysical parameters the absence of the astrophysical contributions in the angular power spectrum results in a bias for  $B_{1\text{Mpc}}$  and  $n_B$ , which would lead to a tentative detection of a few nG amplitude with an  $n_B \sim -1$  spectrum.

#### B. Constraints on causal fields

The results of the analysis with WMAP 7 and SPT data shows that positive spectral indices  $n_B > 0$  are allowed only with a very small PMF amplitude.

In the following we constrain the amplitude for  $n_B = 0, 2, 3$ . The results of the analysis are:  $B_{1\text{Mpc}} < 5.6 \times 10^{-1}$  nGauss for  $n_B = 0$ ,  $B_{1\text{Mpc}} < 6.6 \times 10^{-3}$  nGauss for

$n_B = 2$  and  $B_{1\text{Mpc}} < 7 \times 10^{-4}$  nGauss for  $n_B = 3$ . As expected from the results of the analysis for variable spectral index the constraints on  $B_{1\text{Mpc}}$  are much stronger than the generic ones. These tight limits will be important for their implications on PMF generation and evolution.

### V. IMPLICATIONS FOR *PLANCK*

In our previous work [10] we have analyzed the capability of the *Planck* satellite [52] to constrain the amplitude of PMF. In Ref. [10] we have performed a MCMC analysis with *Planck* simulated data with vanishing PMF obtaining  $B_{1\text{Mpc}} < 2.7$  nG at 95% confidence level, a constraint stronger than the present one obtained with the combination of WMAP 7 and SPT data. However the two constraints are not directly comparable, in fact in our analysis of *Planck* forecasts we did not include any contamination by astrophysical contributions of the simulated data as it should instead be expected in real data on small angular scales. In particular, the presence of extragalactic contributions on small angular scales has an impact on *Planck* data and might degrade the constraint on PMF amplitude. We now investigate this issue following the treatment of astrophysical contamination, which has been developed for *Planck* data, given in Ref. [36]. In Ref. [36] are considered the three main contributions for *Planck* frequencies from 70 to 353 GHz: the Poissonian term both for radio and infrared galaxies, the clustering term for infrared galaxies and the TSZ. The contributions to the angular power spectrum are modelled with empirical parametrizations based on *Planck* early data results for the point sources and on theoretical models for the TSZ. We performed a MCMC analysis with *Planck* simulated data with the combination of five frequencies, 70, 100, 143, 217, 353 GHz with updated beams and noise characteristics from [53], [54]. In Fig. 5 we show the comparison between the results on PMF amplitude with and without astrophysical contamination. The result on PMF amplitude without astrophysical contamination is  $B_{1\text{Mpc}} < 2.4$  nG and is represented by the dashed line in Fig. 5. This result, without astrophysical contamination, is updated with respect to our previous work since the simulated data are now based on an extended mission duration and the sensitivities and angular resolutions are updated to the last in flight real performances. The results of the case where the astrophysical contamination is considered are represented by the solid line in Fig. 5, we note how as expected the constraints on PMF amplitude are degraded and in particular are  $B_{1\text{Mpc}} < 3.6$  nG at the 95% confidence level.

### VI. CONCLUSIONS

We have studied the constraints on a stochastic background of PMF by a combination of WMAP 7 and SPT

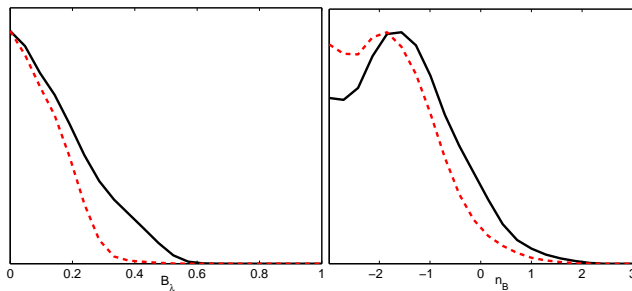


FIG. 5. Constraints with *Planck* simulated data with (black solid line) and without (red-dashed line) extragalactic residual contribution. We followed the treatment for the residual contribution as in [36] for both the simulated data and the MCMC analysis.

data. On the basis of previous works, we have included in the analysis only the dominant magnetic contributions by scalar and vector magnetized perturbations. In order to not introduce biases in the magnetic parameter constraints we have considered the contamination by astrophysical residuals of the SPT data. The dominant contributions are given by unresolved point sources and in particular radio and infrared galaxies and by galaxy clusters. We have considered both Poissonian and clustering terms for point sources and the SZ effect for the galaxy cluster contribution. To model the contributions to the angular power spectrum of the three signals we have used the templates provided by the SPT collaboration [32, 45]. These templates require three additional parameters to describe the amplitude of the three astrophysical signals. Therefore together with standard six cosmological parameters we have included in our analysis not only the PMF amplitude and spectral index but also the three new parameters for the astrophysical residuals. We performed a MCMC analysis with the eleven cosmological, magnetic and astrophysical parameters and we constrain  $B_{1\text{Mpc}} < 3.5$  nG with preferred positive spectral index at 95% confidence level. The results do not show any strong degeneracy between magnetic and astrophysical parameters which is compatible with the multipole range of SPT

data ( $\ell_{\text{max}} \sim 3000$ ) used. Comparing these results with the previous constraints with data by WMAP7, ACBAR, QUAD and BICEP [10, 12], which were of the order of  $B_{1\text{Mpc}} < 5$  nG, we note a very good improvement for the constraint on  $B_{1\text{Mpc}}$  with the use of SPT data.

We updated the forecasts for *Planck* that we obtained in our previous work [10], considering an extended mission duration and the updated in flight performances we obtained  $B_{1\text{Mpc}} < 2.4$  nG. This results do not consider the astrophysical contamination of the data which instead will likely affects real *Planck* data. Therefore to obtain more realistic forecasts we performed an analysis which takes into account extragalactic residual contributions to *Planck* simulated data following the treatment in [36]. The results we obtained show a significant degradation of the constraints on PMF due to the presence of extragalactic contributions:  $B_{1\text{Mpc}} < 3.6$  nG. The constraint from *Planck* realistic simulated data is therefore compatible with the one we obtained with the combination of WMAP and SPT.

We investigated the impact of astrophysical residuals on the magnetic parameters with a MCMC analysis using the same data but neglecting all the three astrophysical signals. The results show biases in all parameters, both the cosmological but most of all in the magnetic ones. In particular the PMF amplitude shows a tentative detection of few nG. This result obviously is not related with the nature of PMF but it is completely due to the astrophysical contamination and demonstrates the necessity to properly consider possible residuals to constrain PMF with small scale CMB data.

The results presented here confirmed a previously noted trend which prefer negative  $n_B$ . Since  $n_B > 0$  is mainly related to causal generation mechanism, we have shown again how causal fields are allowed with an amplitude much smaller than the nGauss.

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- [1] M. L. Bernet, F. Miniati, S. J. Lilly, P. P. Kronberg and M. Dessauges-Zavadsky, *Nature (London)* **454**, 302, (2008).
  - [2] A. M. Wolfe, R. A. Jorgenson, T. Robishaw, C. Heiles and J. X. Prochaska, *Nature (London)* **455**, 638 (2008).
  - [3] K. Dolag, M. Kachelriess, S. Ostapchenko and R. Tomas, *Astrophys. J.* **727**, L4 (2000).
  - [4] F. Tavecchio, G. Ghisellini, L. Foschini, G. Bonnoli, G. Ghirlanda and P. Coppi, *Mon. Not. R. Astron. Soc.* **406**, L70 (2010).
  - [5] A. Neronov and I. Vovk, *Science* Vol. **328**, 5974, 73 (2010).
  - [6] A. M. Taylor, I. Vovk and A. Neronov, *Astronomy & Astrophysics*, **529**, A144 (2011).
  - [7] I. Vovk, A. M. Taylor, D. Semikoz and A. Neronov, *Astrophys. J.* **747**, L14 (2012).
  - [8] D. G. Yamazaki, K. Ichiki, T. Kajino and G. J. Mathews, *Astrophys. J.* **646**, 719 (2006).
  - [9] D. G. Yamazaki, K. Ichiki, T. Kajino and G. J. Mathews, *Phys. Rev. D* **81** 023008 (2010).
  - [10] D. Paoletti and F. Finelli, *Phys. Rev. D* **83**, 123533 (2011).
  - [11] D.G. Yamazaki, T.Kajino, G.J. Mathews and K.Ichiki arXiv:1204.3699 (2012).
  - [12] J. R. Shaw and A. Lewis, *Phys. Rev. D* **86**, 043510 (2012).

- [13] K. Jedamzik and T. Abel, arXiv:1108.2517 (2011).
- [14] D. Paoletti, F. Finelli and F. Paci, Mon. Not. R. Astron. Soc. **396**, 523 (2009).
- [15] J. R. Shaw and A. Lewis, Phys. Rev. D **81**, 043517 (2010).
- [16] S. Koh and C. H. Lee, Phys. Rev. D **62**, 083509 (2000).
- [17] T. Kahniashvili and B. Ratra, Phys. Rev. D **75**, 023002 (2007).
- [18] M. Giovannini and K. Kunze, Phys. Rev. D **77**, 063003 (2008).
- [19] F. Finelli, F. Paci and D. Paoletti, Phys.Rev. D **78**, 023510 (2008).
- [20] C. Bonvin and C. Caprini, J. Cosmol. Astropart. Phys. 05 (2010) 022.
- [21] K. Subramanian and J. D. Barrow, Phys. Rev. D **58**, 083502 (1998).
- [22] A. Mack, T. Kahniashvili and A. Kosowsky, Phys. Rev. D **65**, 123004 (2002).
- [23] A. Lewis, Phys. Rev. D **70**, 043011 (2004).
- [24] R. Durrer, P. G. Ferreira and T. Kahniashvili, Phys. Rev. D **61**, 043001 (2000).
- [25] C. Caprini, R. Durrer and T. Kahniashvili, Phys. Rev. D **69**, 063006 (2004).
- [26] C. Caprini, F. Finelli, D. Paoletti and A. Riotto, J. Cosmol. Astropart. Phys. 06 (2009) 021.
- [27] T. R. Seshadri and K. Subramanian, Phys. Rev. Lett. **103**, 081303 (2009).
- [28] P. Trivedi, T. R. Seshadri and K. Subramanian, Phys. Rev. Lett. **108**, 231301 (2012).
- [29] C. L. Reichard et al., Astrophys. J. **694**, 1200 (2009).
- [30] M. L. Brown *et al.* [QUaD collaboration], Astrophys. J. **705**, 978 (2009).
- [31] H. C. Chiang et al., Astrophys.J. **711**, 1123, (2010).
- [32] R. Keisler et al., Astrophys. J. **743**, 28 (2011).
- [33] C. L. Reichardt et al., Astrophys. J. **755**, 70 (2012).
- [34] C. Dvorkin, M. Wyman, W. Hu, Phys.Rev. D **84**, 123519, (2011).
- [35] K. Jedamzik, V. Katalinic and A. Olinto, Phys. Rev. D **55**, 4582 (1997).
- [36] D. Paoletti, N. Aghanim, M. Douspis, F. Finelli, G. De Zotti, G. Lagache and A. Penin, arXiv:1112.3260 (2011).
- [37] P. Serra, A. Cooray, A. Amblard, L. Pagano and A. Melchiorri, Phys. Rev. D, **78**, 043004 (2008).
- [38] Planck Collaboration, Astron. Astrophys. **536**, A13 (2011).
- [39] Planck Collaboration, Astron. Astrophys. **536**, A18 (2011).
- [40] M. Millea, O. Dore, J. Dudley, G. Holder, L. Knox, L. Shaw, Y.-S. Song and O. Zahn, Astrophys. J. **746**, 4 (2012).
- [41] G. E. Addison et al., Astrophys. J. **752**, 120 (2012).
- [42] J. Q. Xia, M. Negrello, A. Lapi, G. de Zotti, L. Danese & M. Viel, Mon. Not. R. Astron. Soc. **422**, 1324 (2012).
- [43] R. A. Sunyaev and Y. B. Zeldovich, Astrophysics and Space Science **7**, 3 (1970); Annual review of astronomy and astrophysics **18**, 537 (1980).
- [44] R. A. Sunyaev and Y. B. Zeldovich, Comment Astrop. and Space Phys. **4**, 173 (1972).
- [45] [pole.uchicago.edu/public/data/Keisler11/index.html](http://pole.uchicago.edu/public/data/Keisler11/index.html).
- [46] N. Jarosik et al., Astrophys. J. Suppl. Ser. **192**, 14 (2011).
- [47] D. Larson et al., Astrophys. J. Suppl. Ser. **192**, 16 (2011).
- [48] A. Lewis and S. Bridle, Phys. Rev. D **66**, 103511 (2002).
- [49] W. K. Hastings, Biometrika **57**, 97 (1970).
- [50] A. Gelman and D. B. Rubin, Statistical Science **7**, 457 (1992).
- [51] E. Komatsu and U. Seljak, Mon. Not. R. Astron. Soc. **336**, 1256 (2002).
- [52] [Planck Collaboration], “Planck: The scientific programme,”, ArXiv: 0604.069 (2006).
- [53] Planck HFI Core Team, Astron. Astrophys. **536**, A6 (2011).
- [54] A. Mennella et al., Astron. Astrophys. **536** A3 (2011).